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A Review of Surface Haptics: Enabling Tactile Effects on Touch Surfaces

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Abstract—We review the current technology underlying surface haptics that converts passive touch surfaces to active ones (machine haptics), our perception of tactile stimuli displayed through active touch surfaces (human haptics), their potential applications (human-machine interaction), and finally the challenges ahead of us in making them available through commercial systems. This review primarily covers the tactile interactions of human fingers or hands with surface-haptics displays by focusing on the three most popular actuation methods: vibrotactile, electrostatic, and ultrasonic.

Index Terms—surface haptics, tactile feedback, vibrotactile, electrovibration, ultrasonic, friction modulation, review, state of the art.

1 INTRODUCTION

HAPTICS for interactive touch surfaces, also known as surface haptics, is a new area of research in the field of haptics. The goal of surface haptics is to generate tactile effects on touch surfaces such as those used in mobile phones, tablets, kiosks and information displays, and front panels of new generation home appliances and cars.

Integration of haptics into touch surfaces will result in new applications in user interface design, online shopping, gaming and entertainment, education, arts, and more (see Fig. 1). Imagine that you can feel the fabric of clothes as you purchase them online on a tablet, that you can feel the edges of buttons on your mobile phone as you dial without looking, that you can play chess on an interactive touch surface and feel a frictional resistance when you make an incorrect move, that you can feel the detents of a digital knob on the touch surface of your car as you rotate it, that a visually impaired person navigates in a building using a haptic map on a tablet, or that your children feel an exotic animal on an interactive touchscreen in a classroom. As obvious from the examples above, surface haptics is a new and exciting area of research and the number of potential applications of this technology is countless.

This review primarily covers the tactile interactions of human fingers or hands with surface-haptics displays by focusing on the three most popular actuation methods: vibrotactile, electrostatic, and ultrasonic. We intentionally excluded some other less-common actuation methods such as electromagnetic actuation (e.g., [1]) and methods utilizing fluidic pressure [2] as well as kinesthetic haptic interactions (that do not primarily involve the tactile channel)

with shape-changing surfaces (e.g., [3]), indirect haptic interactions with touch surfaces such as mid-air haptics via acoustic radiation pressure (e.g., [4]) and through hand-held devices such as pen/stylus from our review (e.g., [5]).



Fig. 1. Applications of surface haptics span many areas including online shopping, education, tele-touch, games and entertainment, tactile user interfaces, data visualization, art appreciation, and aid for blind and visually impaired

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We review the current state of the art in terms of 1) machine haptics: technologies to generate tactile stimuli on touch surfaces and the physics behind them, 2) human haptics: our tactile perception of those stimuli, 3) human-machine haptics: interactions between humans and surface haptics technologies, leading to rendering of virtual shapes, textures, and controllers with potential applications in the areas discussed above.

2 MACHINE HAPTICS

Here, we provide an introduction to the current actuation technologies enabling tactile feedback on touch surfaces. We first group them based on the direction of stimulation and then briefly discuss how each technology works.

2.1 Classification

From the technological point of view, the goal of surface haptics is to design and develop new devices in order to display tactile feedback to the users by modulating the interaction forces between the finger and the touch surface. In general, the current actuation technologies can be grouped based on the direction in which the finger is stimulated by the interaction forces, as depicted in Fig. 2: a) normal to the surface (F_n), b) tangential to the surface (F_t and F_o). In Fig. 3, we present our approach of further classifying the current technologies based on the general force decomposition given in Fig. 2.

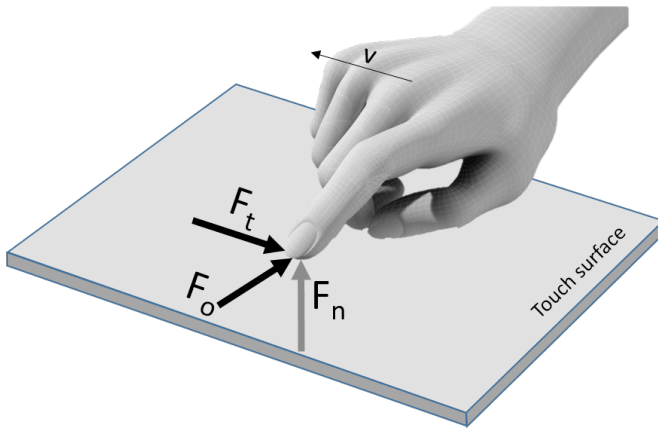


Fig. 2. The components of the force acting on the finger during haptic interactions with a touch surface

When the stimulation is in the normal direction, an actuator placed in the periphery of the surface creates a mechanical vibration that propagates inside the material and reaches the finger [6]. This type of stimulation, denoted by *normal vibration*, is directly detectable by our tactile system if it occurs at a frequency below 1 kHz. In fact, vibration actuators are already embedded in mobile phones today for this purpose and used to alert the user about incoming calls and to provide confirmation for button press events. Although it is highly difficult to generate complex tactile effects using these simple actuators, they have been used by manufacturers due to their low-cost and low energy requirements.

Using multiple actuators allows for more sophisticated stimulation techniques in the normal direction that lead to unique tactile effects. For example, imposing multiple vibrations on the surface with adequate amplitude or phase modulation provides a vibration sensation midway between the actual stimulated points, which can either be static or moving. This so-called *tactile phantom sensation* has been already studied intensively and used for many applications [7]; see [8] for a review. We further discuss the application

of this concept to surface haptics in Section 2.3.1. Other techniques are also possible mostly to localize vibrations to a small region on the surface by obtaining constructive and destructive waves where needed (see Section 2.3.2). The theory behind this principle has been investigated under the names of *inverse filtering* [9] and *modal composition* [10], [11].

Instead of displaying continuous vibrations, short vibration *pulses* can be used to generate tactile effects in the normal direction, which is more challenging due to the resonating nature of the touch surface. The mechanical excitation of the surface produces echoes, which have to be cancelled out in order to obtain a short burst of normal displacement at a specific location. For that purpose, multiple actuators are placed on the surface, and their control signals are synchronized in order to create constructive and destructive interference. The references for these signals can be deduced from the *time reversal* theory, as in [12], [13].

It is also possible to modulate the contact force in the tangential plane to display tactile effects if there is a relative displacement between the finger and the tactile surface. For example, due to the viscoelastic properties of finger pulp, the lateral movement of the tactile surface can induce tangential forces inside the finger pulp and thus *lateral vibrations*. By modulating this lateral movement as a function of the finger displacement, it is even possible to render virtual textures on a tactile surface [14]. Indeed, by means of a phenomenon called *causality inversion*, the forces produced by the lateral movement of the tactile surface can be matched to those produced by a real textured surface when a finger slides on it.

Alternatively, researchers have devised ways to dynamically create *friction modulation* between the tactile surface and the finger sliding on its surface. This can be, for example, achieved by using actuators that generate *ultrasonic waves* on the tactile surface [15], [16], [17], [18]. The vibration reduces the friction coefficient, a phenomenon called *active lubrication*, because the finger is in intermittent contact with the plate. Using this approach, it is possible to simply turn the actuation on and off to generate relatively simple tactile effects in open loop or to control the amplitude of vibrations in closed loop to generate more complex tactile effects.

Instead of decreasing the friction via ultrasonic actuation, it is possible to increase it by using *electrostatic* actuation [19], [20], [21], [22]. This involves applying a voltage to the conductive layer of a capacitive touchscreen to generate electrostatic attractive forces in the normal direction between its surface and a finger sliding on it, which leads to an increase in frictional forces applied to the finger opposite to the direction of movement. Although the magnitude of this electrostatic force in the normal direction is small relative to the normal load applied by the finger, it results in a perceivable frictional force in the tangential direction when the finger slides on the touch screen. This frictional force can be modulated to generate different tactile effects by altering the amplitude, frequency and waveform of the voltage signal applied to the touchscreen.

In order to obtain a *net tangential force* on the plane of the tactile surface (i.e., vectorial summation of F_t and F_o in Fig. 2) even without any finger displacement, one can physically displace the tactile surface in the direction tangent to the finger movement on the same plane while

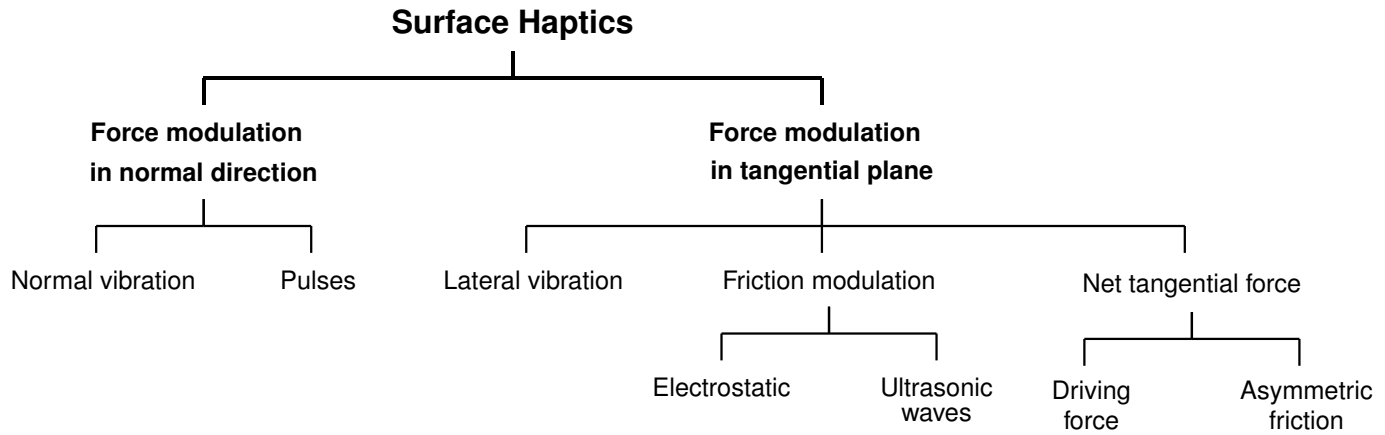


Fig. 3. Classification of the current technologies for surface haptics displays based on the stimulation direction and method.

modulating the friction using either ultrasonic or electrostatic actuation. This technique, named *asymmetric friction*, can produce net forces with very low lateral displacements of the surface [23]. Finally, by combining bending modes at high frequency of the surface, it is also possible to produce such a net force, by using *elliptical movement* of the surface's particles [24].

Figure 3 presents the classification of the methods proposed in the literature to create surface haptics displays. The next section presents the type of actuators used to create tactile stimuli on touch surfaces, followed by an in-depth discussion of the different stimulation methods given in this figure.

2.2 Actuator Technologies

In most of the cases presented in Figure 3, the forces created at the contact area are produced through the medium that is constituted by the touch surface itself. Actuators can convert electrical power into mechanical power; they are placed in such a position that their action can control the contact forces.

There are many different types of actuators for generating tactile stimuli on touch surfaces. The *electromagnetic actuators* generate a force which is proportional to a current. Among others, *vibrations motors* have been used most widely for surface haptics applications. A vibration motor is a dc-motor that has a rotor with eccentric mass distribution (so also called ERM; eccentric rotating mass), which creates rotational movement to the housing and is in turn perceived as a vibration by the user. Vibration motors can generate relatively large vibrations and be made in diverse sizes and shapes. The frequency of vibration is controllable by changing the voltage. However, the amplitude (in displacement) is constant [25], which restricts the diversity of vibration waveforms that can be rendered. Furthermore, they generally have large actuation lags. Also popular are *voice coil actuators*, which are similar to speakers used in audio systems. They can produce any waveforms with fast responses. Linear resonance actuators (LRAs) are a special type of voice coil actuators designed in a very small size for mobile devices. While it has a faster response than an

ERM, its frequency bandwidth is generally very narrow. In general, electromagnetic actuators are usually suitable for low-to-mid range actuation frequencies (with respect to human tactile perception), have low voltage requirements, and have high displacement/low force characteristics (see [26] for a detailed review).

Piezoelectric actuators are also frequently used for surface haptics. They are more suitable for actuation of touch surfaces at high frequencies, and can generate high forces but at low displacement. They are also compact and can be easily mounted on a touch screen. However, they typically require very high voltage input, and are brittle and weak to external shock; major drawbacks preventing their commercial adoption.

Those that have received attention more recently include *electroactive polymers* – like polyvinylidene fluoride –, which change their shape in volume when an electrical field is applied to them. Voltage requirements are often very high, but their softness allows them to be prepared on a large surface, in various sizes and forms. Finally, *electrostatic actuators* produce a force which is proportional to the square of the voltage. The level of force is typically very low, but they can be used for high frequency surface haptics applications. The main advantage here is that electrostatic forces can be generated on the finger's skin directly, without taking into account the medium.

Table 1 provides examples of the aforementioned actuator technologies for each method presented in Figure 3, while more details are given on their operating principles in the next sections.

2.3 Force Modulation in the Normal Direction

When a touch screen is actuated by a simple vibration motor as in mobile devices, a vibration wave propagating in the screen reaches the finger or hand in contact with its surface. Although this approach is sufficient for simple vibrotactile effects such as alerting the user about incoming call and receiving confirmation for button press, researchers have developed more sophisticated techniques to provide more interesting, useful, and salient vibrotactile effects, often using multiple actuators. Here we describe two such

TABLE 1
Examples of actuator technologies used for surface haptics

Actuator technology	Frequency	Force output	Displ. output	Voltage req.	Normal Vibration	Pulses	Lateral Vibration	Friction Modulation	Driving Force	Asymmetric Friction
Electromagnetic	L	L	H	L	[6], [27]	[10], [12]	[28], [29]			[23], [30], [31]
Piezoelectric	H	H	L	H	[9], [27], [32], [33], [34]	[35]	[28], [36]	[16], [18], [30], [37], [38]	[39], [24]	[23], [30], [40]
Electroactive Polymer	L	L	H	H	[41], [42]					
Electrostatic force	H	L	L	H				[22], [43], [44]		[40]

approaches: one is to generate illusory tactile sensations between the actual excitation positions and the other is to localize vibration to only a small area on the touch surface.

2.3.1 Tactile Phantom Sensations on Touch Surfaces

In general, the spatiotemporal characteristics of human tactile perception must be adequately reflected in designing surface haptics displays and associated interactions. In spite of high human tactile acuity (spatial resolution of 1–2 mm at the fingertip [45]), developing spatially-dense and distributed surface haptics displays is out of reach of current technology. One effective and popular way for generating such spatial tactile feedback is to exploit a perceptual illusion called *phantom sensation* or *funneling illusion*. A phantom sensation refers to an illusory tactile sensation that occurs midway between two or more distant tactile stimuli [46]. Phantom sensation is an effective method to improve the spatial resolution of a surface haptics display using only a few actuators.

According to the taxonomy of tactile phantom sensations [8], those mediated through a rigid object such as a touch surface are relevant to surface haptics. In this case, illusory tactile effects are perceived when the finger skin is in contact with the surface that is vibrated by multiple actuators simultaneously or in sequence. Such phantom sensations can be elicited on a line between two stimulation points (1D) or within a polygon surrounded by more stimulation points (2D). A phantom sensation can stay at one point (stationary) or move on the surface (moving). A moving phantom sensation is similar in its notion to apparent tactile motion and sensory saltation [47]. The perceived location of an illusory tactile sensation is controlled by adjusting either the amplitudes of the stimuli (amplitude inhibition) or their time gap (temporal inhibition) [46], or both.

Rendering stationary phantom sensations on a touch surface requires vibration damping mechanisms, such as those in [48], [49], [50], [51]. This situation is similar to stimulating the skin directly, without vibrations generated by multiple actuators interfering with each other. It was demonstrated that stationary phantom sensations could be elicited on the surface of a mobile phone by controlling four vibration actuators with silicon-based dampers positioned at its corners [8]. The identification accuracy of the positions

of the stationary phantom sensations was measured, and the distributions of the perceived positions were estimated.

Without such dampers, only moving phantom sensations can be generated on a touch surface [8], and most previous studies on surface haptics have focused on this type of stimulation. In this case, vibrations produced by multiple actuators are overlapped over the surface, and they are unable to provide spatially separate tactile cues required for eliciting stationary phantom sensations. Instead, we can vary the relative intensity or phase differences between the actuators over time, and such contrast effects lead to the perception of moving tactile sensations in spite of the fixed actuator positions. Kim et al. [52] attached two ERMs at the two long ends of a mobile phone and proposed a rendering algorithm for 1D moving phantom sensations based on temporal inhibition. The authors then designed and fabricated a processor dedicated to the proposed rendering algorithm [53]. In contrast, Seo et al. [54] used two LRAs and demonstrated 1D moving phantom sensations using amplitude inhibition. They designed general synthesis functions using polynomials and examined the effects of their parameters on salient perceptual measures, such as sensation movement distance, velocity variation, intensity variation, and the confidence rating of moving sensation [55]. These results provide design guidelines of 1D moving phantom sensations with desired perceptual properties. In [56], Kang et al. used piezoelectric actuators and demonstrated that the amplitude profile has a significant effect on several perceptual qualities (accuracy, expression validity, and expression refinement). They also carried out simulations and experiments for vibration propagation on a thin plate and showed that amplitude inhibition with frequency sweep led to the smoothest moving sensations [57]. Seo et al. [58] recently extended their earlier work to a 2D case (called edge flows) by using four LRAs attached to the corners of a mobile phone to render moving phantom sensations following its edges.

2.3.2 Localized Stimulation on Touch Surfaces

In order to generate localized tactile effects on touch surfaces, the authors in [27] altered the geometrical parameters of the surface (especially the width to make it narrow) in order to confine the vibration at the location of the actuator.

The resulting surface had the dimensions of $200 \times 25 \times 0.5$ mm³. The solution proposed in this study is robust, but it is applicable to narrow plates and the actuator should be transparent so as not to obstruct the view. In [41], the authors cover the entire surface with a relaxor ferroelectric polymer (RFP) transparent film, and produce stimulation based on the fretting phenomenon. They could create localized vibrations at a frequency of 500 Hz, with an amplitude of $1 \mu\text{m}$ for a voltage amplitude of 200 V.

In [33], the authors attached four piezoelectric patches to the edges of a touch screen to control out-of-plane vibrations and display localized haptic feedback to the user. For this purpose, a vibration map of the touch surface was constructed in advance and then vibrotactile haptic feedback was displayed to the user using this map during real-time interaction with the finger. The size of the touch surface was $743 \times 447 \times 3$ mm³. In order to display localized haptic feedback, they divided the surface into 84 grid points and then maximized the vibration at the contact point, while minimizing it at the grid points around it.

As an alternative to the look-up table method suggested in [33], vibration modes of a touch surface can be superimposed to create a vibration pattern that is detectable by the fingertip. In [10], 34 electromagnetic actuators, placed at the periphery of a glass plate with dimensions of $268 \times 170 \times 0.7$ mm³, could control 34 vibration modes, and create a pulse on a square spot of 50×50 mm². To increase the contrast (the ratio of the vibration amplitude at the focus point to the amplitude anywhere else on the plate), the time reversal technique can be used. In [12], for instance, the authors used 4 electromagnetic actuators to create a 3 ms duration pulse with an amplitude of 1 mm and a spot size of 20 mm in diameter on a glass plate with dimensions of $420 \times 420 \times 2$ mm³. A higher contrast was obtained in [35] with 32 piezoelectric actuators. The authors could create a pulse with an amplitude of $7 \mu\text{m}$ and a spot diameter of 5.2 mm on a plate with dimensions of $148 \times 210 \times 0.5$ mm³.

2.4 Force Modulation in the Tangential Plane

2.4.1 Lateral Vibration

In-plane vibrations of a touch surface can also produce tactile stimulation on the finger pad. Indeed, [36] shows that displacement of the skin by lateral vibrations can produce the same lateral forces as when interacting with a rough texture, and can elicit a similar sensation of roughness for a virtual surface. The advantage of lateral vibrations is that actuators can be placed at the periphery of the touched surface, as in [28], so they do not have to be transparent. Electromagnetic [29] and piezoelectric [28] actuators have been used for that purpose so far.

2.4.2 Friction Modulation

Instead of producing a lateral force directly by using actuators that vibrate the touch surface in the tangential plane, it is possible to modulate the friction between the fingertip placed on a pad and the touch surface using surface acoustic waves (SAW) as in [59]. This solution is efficient only when the finger is moving on the surface, which is a limitation compared with lateral vibrations. However, the lateral force is obtained indirectly by friction modulation,

which can be more easily achieved than the direct lateral force modulation. Alternatively, two more methods have been introduced in the literature to directly control the friction on a touch surface: by using electrostatic forces and ultrasonic vibrations.

Electrostatic Actuation. The electrical attraction between human skin and a charged surface is was first reported by Elisha Gray in a patent in 1875 [60] and then Johnsen and Rahbek in 1923 [61]. Approximately thirty years later, Mallinckrodt discovered by accident that dragging a dry finger over a conductive surface covered with a thin insulating layer and in the presence of the alternating voltage can increase friction during touch [62]. He explained this phenomenon based on the well-known principle of the parallel plate capacitor. Later, Grimnes named this phenomenon electrovibration (electrically induced vibrations) and reported that surface roughness and dryness of finger skin could affect the perceived haptic effects [19]. Afterwards, Strong and Troxel [20] developed an electrotactile display consisting of an array of electrodes insulated with a thin layer of dielectric. Using friction induced by electrostatic attraction force, they generated texture sensations on the touch surface. Beebe et al. [21] developed a polyimide-on-silicon electrostatic fingertip tactile display using lithographic microfabrication. They were able to generate tactile sensations on this thin and durable display using 200–600 V voltage pulses and reported the perception at the fingertip as sticky. Later, Tang and Beebe [63] performed experiments for detection threshold, line separation and pattern recognition with visually impaired subjects. The subjects successfully differentiated simple tactile patterns by tactile exploration.

More recently, Bau et al. [64] and Linjama et al. [65] showed that electrovibration can be delivered through a commercial capacitive touch screen, which demonstrates the viability of this technology on large surfaces. The surface capacitive touchscreen used in those studies consists of a glass substrate, coated with Indium Tin Oxide (ITO) as a conductive layer and Silicon Dioxide (SiO_2) as an insulating layer. When an alternating voltage is applied to its conductive layer (see Fig. 4a), as the human body is also an electrical conductor, touching the surface of the screen results in an attraction force between finger and surface of touchscreen due to the induction of charges with opposite signs on the insulating layer of the glass substrate and the finger. In fact, this is only one of the ways of generating electrostatic attractive force between a human fingerpad and a touch surface. Bau and Poupyrev [66] proposed REVEL, in which the voltage was applied to the user's finger rather than the conductive layer of the touchscreen (Fig. 4b). Hence, REVEL is based on the principle of, as the authors call it, *reverse electrovibration* and enables to change the tactile feeling of real touch surfaces by augmenting them with virtual tactile textures.

It is also possible to generate electrostatic attractive forces between a finger and an object sliding on a touch surface (Fig. 4c). For example, Yamamoto et al. [43] developed an electrostatic tactile display that consists of a conductive pad sliding on a touch surface with embedded conductive electrodes. The sliding pad was not explicitly grounded, but a pair of positive and negative alternating

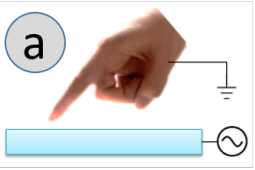
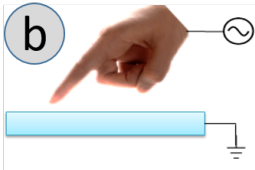
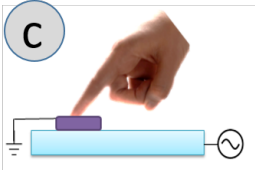
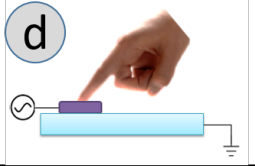
Method	Voltage	Ground
	Touch Surface	User
	User	Touch Surface
	Touch Surface	Object
	Object	Touch Surface

Fig. 4. Different methods of grounding for electrostatic actuation

voltage signals were applied to the electrodes to make the voltage balance around 0 V on the surface of the pad. The display is incorporated into a tactile telepresentation system to enable exploration of remote surface textures with real-time tactile feedback to the user. Later, Nakamura and Yamamoto [67] developed a multiple user system by applying voltage to the sliding pad and grounding the touch surface (Fig. 4d). This technology could in fact open doors to some exciting multi-user applications in gaming, education, and data and information visualization on large scale touch surfaces. For example, a multi-user virtual hockey game was implemented as a demonstration of the technology in [67].

Due to variations in human and environmental impedances, the voltage-induced stimulation may cause tactile feedback with nonuniform intensity on touch surface. Alternatively, a current feedback method was proposed in [68] and the results of the user study showed that it could provide significantly more uniformly perceived intensity of electrovibration as compared with the conventional voltage control method.

While the technology for generating tactile feedback on a touch screen via electrovibration is already in place and straightforward to implement, our knowledge on the underlying contact mechanics and tactile perception are highly limited [77]. This is not surprising since the contact interactions between human skin and a counter surface is already highly complex to investigate even without electrovibration [78], [79], [80], [81]. In the case of electrovibration in particular, the exact mechanism leading to an increase in tangential frictional forces is still not known completely.

To estimate the electrostatic forces between finger pad

and touch screen, models based on parallel-plate capacitor theory have been proposed (see the summary in [82]). These models assume a constant air gap between two surfaces and ignore the rounded shape of the finger pad and the asperities on its surface. On the other hand, to estimate the frictional forces in tangential direction during sliding, the Coulomb model of friction utilizing a constant coefficient of dynamic friction between finger pad and touch screen has been used so far. The increase in tangential force has been explained by simply adding the force due to electrostatic attraction to the normal force applied by the finger, $F_t = \mu(F_n + F_e)$, where μ is the friction coefficient and F_e represents the electrostatic force.

However, friction of human skin against smooth surfaces is governed by the adhesion model of friction [83], [84], which depends on interfacial shear strength and real area of contact as $F_t = \tau A_{real}$. It is highly difficult to measure or estimate the real area of contact, A_{real} , which varies nonlinearly with the normal force. In earlier studies, the real contact area has been taken as the contact area of finger ridges, A_{ridge} , which is smaller than the apparent contact area, $A_{apparent}$, estimated by the fingerprint images using the boundaries of the finger pad in contact with the surface [85]. On the other hand, if the Persson's multi-scale contact theory is considered (see the review of contact theories in [86]), the real area of contact (A_{real}) is, in fact, much smaller than the contact area of finger ridges (A_{ridge}) since only the finger asperities at finer resolution make contacts with the surface. Recently, Persson extended his theory to electroadhesion and derived a mathematical relation for electroadhesive pressure between two conductive surfaces with random roughness in contact for voltage applied to one of the conducting surfaces [87]. He assumed the small slope approximation for the roughness profiles and solved the Laplace equation for electrostatic potential to obtain the pressure due to electroadhesive force for the applied voltage. He used the normal pressure to estimate the real contact area and then the tangential friction force using the adhesion friction model given above.

The application of this approach to the interactions between human finger and touch screen under electroadhesion has been investigated by Ayyildiz et al. [88] and Sirin et al. [89] and verified by the experimental data collected via a custom-made tribometer. These studies show that electrostatic attraction force increases the *real contact area* between fingerpad and touchscreen, leading to an increase in sliding friction force. The authors argue that the artificially generated electrostatic force results in a decrease in interfacial gap and hence the finger asperities make more contacts with the surface of the touch screen at the microscopic scale, leading to an increase in real contact area of the finger. Supporting this claim, Shultz et al. [90] showed that the electrical impedance of the interfacial gap is significantly lower for the stationary finger compared to that of the sliding finger under electroadhesion. In contrast to the argument on increase in real contact area, which is highly difficult to measure and validate experimentally, the decrease in apparent contact area under electrovibration has been already demonstrated experimentally. Sirin et al. [77] conducted an experimental study to investigate the contact evolution between the human finger and a touch screen un-

TABLE 2
Examples of haptic surfaces based on ultrasonic actuation.

Year	Device	Size	Material	Voltage (peak value)	Frequency	Vibration amplitude
2007	StimTac [16]	$83 \times 49 \text{ mm}^2$	Copper	15 V	34.77 kHz	$2.3 \mu\text{m}$
2007	TPad [17]	$\text{Ø}25 \text{ mm}$	Glass	70 V	30 kHz	
2010	LATPad [69]	$75 \times 75 \text{ mm}^2$	Glass	60 V	$\sim 27 \text{ kHz}$	
2012	[70]	$93 \times 65 \text{ mm}^2$	Glass	150 V	31.2 kHz	$1.5 \mu\text{m}$
2013	[71]	$60 \times 40 \text{ mm}^2$	Si Wafer	4 V	31.4 kHz	$1.1 \mu\text{m}$
2013	TPadFire [72]	$165 \times 130 \text{ mm}^2$	Glass	100 V	33.5 kHz	$1.2 \mu\text{m}$
2014	Haptic Sensory Tablet [73]	$270 \times 177 \text{ mm}^2$	Glass			
2015	[74]	$198 \times 138 \text{ mm}^2$	Alu.	20 V	52.4 kHz	$1.25 \mu\text{m}$
2016	eVITA [75]	$154 \times 81 \text{ mm}^2$	Glass	25 V	60 kHz	$1 \mu\text{m}$
2018	[76]	$110 \times 19 \text{ mm}^2$	Glass	45 V	225 kHz	$0.125 \mu\text{m}$

der electrovibration using a robotic set-up and an imaging system. The results show that the effect of electrovibration is only present during full slip but not before slip. Hence, the coefficient of friction increases under electrovibration as expected during full slip, but the apparent contact area is significantly smaller during full slip when compared to that of the condition without electrovibration. It was suggested that the main cause of the increase in friction during full slip is due to an increase in the real contact area and the reduction in apparent area is due to stiffening of the finger skin in the tangential direction.

Ultrasonic Actuation. When a finger slides over a high frequency vibrating plate, the friction that this motion produces decreases as the vibration amplitude increases. This phenomenon, called *active lubrication*, has been first introduced by [91] to develop a tactile stimulator. So far, two different mechanisms have been suggested to explain the cause of friction reduction in ultrasonic tactile displays. [16] proposed that the friction reduction is due to the formation of a squeeze film of air between the finger and the surface. Alternatively, it has been suggested that, when a surface vibrates at an ultrasonic frequency, an intermittent mechanical contact develops between finger and the surface such that the finger bounces on the surface while sliding [92]. A recent study conducted by Wiertlewski et al. [93] using a stroboscope revealed that both mechanisms indeed contribute to the friction reduction. Hence, it appears that the fingertip bounces on a cushion of squeezed film of air. On the other hand, another recent study shows that keeping the vibration acceleration constant rather than the vibration amplitude leads to more uniform air-gap thickness and hence allows for constant reduction in friction [76].

To generate ultrasonic vibration on a touch surface, piezoelectric film actuators are typically glued on the surface and actuated by sinusoidal voltage signals at a resonance frequency above 20 kHz [69]. To efficiently produce this vibration, a stationary bending mode is energized, and a specific design procedure is carried out to optimize the power efficiency [94], [95] and to free the touch surface from non-transparent actuators. In [70], for example, 400 mW of power was required for a voltage amplitude of 150 Vpp to produce a vibration amplitude of $1.5 \mu\text{m}$ at 31 kHz on a $93 \times 65 \times 0.9 \text{ mm}^3$ glass plate. These advances make it possible to create tablets that are able to provide users with tactile feedback via friction modulation [37], [72].

Voltage requirements are typically higher for vibrating a glass plate than a metal substrate of the same size and shape since the glass plate vibrates with more internal damping. To reduce the voltage requirement, it is possible to reduce the piezoelectric material thickness or deposit the piezoelectric active material directly on the substrate. In [71], for example, the authors obtained a vibration amplitude of $1.1 \mu\text{m}$ for a voltage amplitude of 8 Vpp on a silicon substrate of size $60 \times 40 \text{ mm}^2$.

The combination of two vibration modes is also possible at ultrasonic frequency. This can lead to dual-touch tactile stimulator, as in [18], where two vibration modes are controlled in amplitude and phase in order to differentiate the vibration at two points of the plate.

Ultrasonic actuation can provide a higher variation in friction as compared to the electrostatic actuation, while the rendering bandwidth of ultrasonic devices is limited due to its resonating nature [96]. Obviously, there exist a trade-off between the energy efficiency of a device and its bandwidth. To cope for this issue, it is possible to increase the operating frequency, then the necessary bandwidth of the device will be small relative to its resonance frequency, and hence the quality factor of the system will be high. In [38], for example, the authors obtained a quality factor of 775 on a plate made of piezoelectric material resonating at 881 kHz. It is also possible to introduce a feed-forward control as in [97] to compensate for the undesired signal attenuation behaviour of the plate. Furthermore, closed-loop controls can be used to dynamically adapt the level of voltage amplitude in order to compensate for the damping effect of finger on the plate, yet tracking the resonance frequency of the system to enable efficient contact interactions [75], [98].

2.5 Net Tangential Force

It is possible to create shear forces on the bare finger that can be controlled independently of finger speed and direction. In [23], an *asymmetric friction* force was created by a device involving a touch surface that was able to produce active lubrication by ultrasonic actuation via piezo patches and a electromagnetic motor oscillating this surface at 100 Hz in the tangential direction. By synchronizing the friction reduction on the oscillation, forces up to 100 mN could be displayed to the user in this system. In a similar approach, [99] uses electrovibration with oscillations at 1000 Hz to produce lateral forces up to 0.45 N. To obtain controllable

forces on a touch surface in both directions (F_t and F_o in Fig. 2), [30] developed a large area variable friction device, mounted on an impedance controlled planar mechanism. In this way, static and dynamic frictional forces can be controlled as well as the transition between the two regimes. To avoid operating at high frequencies, [31] designed a vibrating surface that follows a saw-tooth like displacement profile with a low frequency of 5 Hz. In this system, the participants could feel more friction when sliding their finger in one direction compared to the other. This solution needs a high amplitude and low frequency movement of the touched surface, which is a limitation of this principle. To cope with this issue, authors in [40] developed a surface haptics display that can simultaneously modulate friction via electrostatic actuation and produce in-plane ultrasonic oscillations at 30 kHz. This system could generate active lateral forces up to 0.4 N. The direction and magnitude of the lateral force can be adjusted by varying the phase between the input signals of in-plane oscillation and the electroadhesion.

It is also possible to generate a *driving force* directly by using two different modal behaviors of a touch surface, promoted at the same time by exciting them at an intermediate frequency between the corresponding two resonance frequencies. For instance, [39] combined an out-of-plate vibration mode of a touch surface with an in-plane lateral one, both having the same resonant frequency (22.3 kHz), to obtain a tilted straight-line motion of the touch surface. The force that develops on the finger is controlled by modulating the relative phase of the two resonances. In this system, lateral forces up to 0.05 N could be exerted on a fixed bare finger. An elliptical motion of the particles, which occurs when a travelling wave is propagating over the plate, can also produce a driving force [24], provided that the friction force can be compensated. For instance, a driving force up to 0.05 N could be generated by using a travelling wave with a frequency of 28.4 kHz and an amplitude of 1.6 μm . This principle has been validated on a beam, but seems difficult to translate to a glass plate.

3 HUMAN HAPTICS

This section covers the studies on surface haptics investigating human tactile perception and contact mechanics between the fingerpad and touch surfaces displaying tactile feedback. As in any other tactile stimuli applied to the finger, it is encoded by the mechanoreceptors first. The encoded signals then travel across a series of neural structures and reach the brain to form the percept.

Due to the limitations in machine haptics today, haptic interactions of a finger with a touch surface are mostly limited to the *tactile* channel. In surface haptics, the surface is generally immovable during interaction. It is extremely challenging to design and implement a surface that makes clearly perceptible displacement, either normal or tangential, while satisfying other requirements such as protection from dust or water. This implies that it is safe to ignore the role of *kinesthetic* perception in most cases and focus on tactile perception. In addition, pressure perception is irrelevant since it requires substantial deformation of the skin. Therefore, vibrotactile and frictional stimuli have the

most prevalent effects in surface haptics. In this regard, we review the literature based on these two kinds of stimuli in the upcoming subsections.

3.1 Vibrotactile Stimuli

To achieve a target perceptual effect, we generate a tactile stimulus using an actuator and deliver it to the user's finger when the finger taps, presses, or slides on the surface. Here the user's finger is already in contact with the surface. The natural mechanical response from the surface always occurs, and it is mixed with the synthetic tactile stimulus. This corresponds to the situation of *haptic augmented reality* [100] though it has been rarely acknowledged in the literature. Therefore, to elicit desired tactile effects, we need salient artificial tactile stimuli that are distinct from the natural tactile stimuli provided by the surface. This is one of the reasons why vibrotactile stimuli have been preferred in the majority of surface haptics applications so far.

The modern theories on vibrotactile perception are based on the four channel theory, which states that glabrous (non-hairy) human skin contains four types of mechanoreceptors (sensory end-organs that detect skin deformation) [101], [102]. If stimulated, each mechanoreceptor fires an electrical pulse, which is transmitted to the cerebral cortex through a nerve. Thus, humans have four kinds of mechanoreceptive channel, and they are classified by sensory adaptation (slow or rapid) and receptive field (small or large). Among the four, two types of fast-adapting (FA) mechanoreceptive channel are in charge of vibrotactile perception. These mechanoreceptors mainly respond to the changes in a stimulus, not much to the steady-state value, due to quick adaptation to the stimulus. This adaptation behavior makes the FA channels suitable for perceiving the time-varying properties of the stimulus.

The PC (Pacini) channel, also called FA (fast adapting) II or P channel, has an end organ called Pacinian corpuscle. The Pacinian corpuscle responds to vibrating mechanical stimuli in a wide frequency band (10–1000 Hz). Its sensitivity depends on many factors. For example, the PC channel has the highest sensitivity at a frequency between 200 Hz and 300 Hz. The receptive field of Pacinian corpuscle is relatively large, and so its spatial acuity is quite low. People generally describe the subjective impression of vibration mediated by the PC channel as a smooth vibration.

The PC channel is capable of energy summation both temporally or spatially. In the temporal domain, a longer stimulus has a lower absolute threshold and so more chance to be perceived than a shorter stimulus of the same intensity. Likewise, a longer stimulus is perceived to be stronger than a shorter stimulus. The same applies to the contact area of a stimulus on the skin, which is called the spatial summation property. Therefore, stimulus duration and contact area are the key parameters that determine various perceptual characteristics of the PC channel.

The other fast-adapting channel is the FA I or NP (Non-Pacini) I channel. This channel has a Meissner corpuscle as the receptor, which is activated by relatively low-frequency (3–100 Hz) vibrations. The Meissner corpuscle has a receptive field smaller than the Pacinian corpuscle, and the FA I channel has better spatial resolution than

the PC channel. The FA I channel also has quite different properties from the PC channel. For example, its detection thresholds are not critically dependent on vibration frequency. The FA I channel is not subject to temporal or spatial summation. The low-frequency vibrations mediated by the FA I channel have a clear fluttering sensation.

The perception of vibrotactile stimuli depends on a large number of factors, such as frequency, amplitude, waveform, body site in contact, duration, contact area, and age. There exist many comprehensive and in-depth reviews on vibrotactile perception [26], [45], [47], [102], [103], [104], and we recommend them for interested readers.

A few notes are to be made. First, the Pacinian corpuscles do not discriminate the stimulation direction of vibration [105]. Thus, the perceptual properties between vibrations in the directions normal and tangential to the surface are very similar. Second, there are fundamental differences between passive touch and active touch. What is described so far is the basis of passive perception of vibrotactile stimuli, where no motor commands are involved. Passive touch is the case when a hand holds a mobile phone or a finger maintains contact with a touchscreen. When hands or fingers move, e.g., for friction perception, underlying perceptual mechanisms and processes are much more complex.

3.2 Frictional Stimuli

Compared to vibrotactile stimuli, tactile perception of frictional stimuli has been studied much less, and little is known about the sensory and neuronal processes behind it. During friction perception, a relative sliding motion between the finger and the surface occurs. There both the normal and tangential forces play a role, and they generate compound strains (both normal and shear) on the fingerpad.

There are several parameters affecting the tactile perception of friction. Obviously, the roughness and material properties of the surface with which the fingerpad is in contact are highly important. The earlier studies in the tribology literature show that friction between skin and a smooth glass surface such as a touch screen is mainly governed by *adhesion*, which is effective at lower normal contact forces [84]. Increasing normal force increases tangential force, while the coefficient of friction decreases and eventually reaches a steady state value [106]. However, it is important to note here that the friction between a smooth surface and a fingerpad varies with many other finger-related parameters such as moisture, velocity, mechanical properties, and fingerprints as well as age and gender (see the reviews in [79], [107]). For example, in interactions with smooth surfaces, accumulated finger moisture at interfacial gap results in softening of the fingerpad, known as plasticization [79], [84], leading to an increase in coefficient of friction.

In the next two subsections, we cover the tactile perception of stimuli displayed by electrostatic and ultrasonic actuation since those are the two prominent approaches for friction modulation on touch surfaces.

Perception of Electro vibration Stimuli. The studies on tactile perception of frictional stimuli on touch surfaces have mainly focused on the estimation of perceptual thresholds for periodic stimuli and its roughness perception so far. As

discussed earlier, electrostatic and ultrasonic actuation are typically used to modulate friction on a touch surface. Bau et al. measured the sensory thresholds of electrovibration using sinusoidal inputs applied at different frequencies [64]. They showed that the change in threshold voltage as a function of frequency followed a U-shaped curve similar to the one observed in vibrotactile studies. Later, Wijekoon et al. [108] investigated the perceived intensity of modulated friction generated by electrovibration. Their experimental results showed that the perceived intensity was logarithmically proportional to the amplitude of the applied voltage signal. Vardar et al. [96], [109] investigated the effect of input voltage waveform on the tactile perception of electrovibration. They showed that humans were more sensitive to tactile stimuli generated by square wave voltage than sinusoidal one at frequencies below 60 Hz. In order to interpret the outcome of these experiments, the force and acceleration data collected from the subjects were analyzed in the frequency domain by taking into account the human vibrotactile sensitivity curve. This detailed analysis showed that the Pacinian channel was the primary psychophysical channel responsible for the detection of the electrovibration stimuli, which is most effective for tactile stimuli at high frequencies around 250 Hz. Hence, the stronger tactile sensation caused by a low-frequency square wave was due to its high-frequency components stimulating the Pacinian channel.

Vardar et al. [110] investigated the interference of multiple tactile stimuli (*tactile masking*) under electrovibration. They conducted psychophysical experiments and showed that masking effectiveness was larger with pedestal masking than simultaneous one. They also showed that sharpness perception of virtual edges displayed on touch screens depends on the *haptic contrast* between background and foreground stimuli, similar to the way it has been observed in vision studies, which varies as a function of masking amplitude and activation levels of frequency-dependent psychophysical channels.

Ryo et al. [111] attached piezoactuators to a capacitive touch screen and investigated the effect of *in-site* vibrotactile masking on tactile perception of electrovibration. They showed that the absolute threshold of electrovibration increases in the form of a ramp function as the intensity of the masking stimulus (mechanical vibration) increased. The masking effect was more prominent when the frequency of both the target and the masking stimulus was the same. Jamalzadeh et al. [112] investigated whether it is possible to change the detection threshold of electrovibration at fingertip of the index finger via *remote masking*, i.e. by applying a (mechanical) vibrotactile stimulus on the proximal phalanx of the same finger. The masking stimuli were generated by a voice coil (Haptuator). The results of their experimental study with 8 participants showed that vibrotactile masking stimuli generated sub-threshold vibrations around the fingertip and, hence, did not mechanically interfere with the electrovibration stimulus. However, there was a clear psychophysical masking effect due to central neural processes. The electrovibration absolute threshold increased approximately 0.19 dB per dB increase in the masking level.

The number of studies on roughness perception of periodic stimuli rendered on a touch surface by electrovibra-

tion is only a few and the underlying perceptual mechanisms have not been established yet. Vardar et al. [113] investigated the roughness perception of periodic gratings displayed by electrovibration. They compared four waveforms: sine, square, triangular and saw-toothed waves with spatial period varying from 0.6 to 8 mm. The width of periodic high friction regimes (analogous to ridge width) was taken as 0.5 mm, while that of the low friction ones (analogous to groove width) was varied. The results showed that the square waveform was perceived as the roughest, while there was no significant difference between the other three waveforms. The perceived roughness decreased with increasing spatial period in general, though a modest U-shaped trend was observed with a peak value around 2 mm. They also reported that the roughness perception of periodic gratings correlates best with the rate of change in tangential force, similar to real gratings [114]. Isleyen et al. [115] compared the roughness perception of real gratings made of plexiglass with virtual gratings displayed by electrovibration through a touch screen. The results of their experimental study clearly showed that the roughness perception of real and virtual gratings are different. They argued that this difference can be explained by the amount of fingerpad penetration into the gratings. For real gratings, penetration increased the tangential forces acting on the finger, whereas for virtual ones where skin penetration is absent, the tangential forces decreased with spatial period. Supporting this claim, they also found that increasing normal force increases the perceived roughness of real gratings while it causes an opposite effect for the virtual gratings. Ito et al. [116] investigated the effect of combining vibrotactile and electrostatic stimuli in different ratios on tactile roughness perception of virtual sinusoidal gratings. Their experimental results showed that a vibrotactile stimulus with a slight variable-friction stimulus is perceptually more effective for displaying gratings with surface wavelengths greater than or equal to 1.0 mm.

Recently, Ozdamar et al. [117] investigated the tactile perception of a step change in friction and the underlying contact mechanics using a custom-made set-up including a high speed and frame-rate camera for finger imaging. The experimental results showed that the participants perceived rising friction stronger than falling friction, and both the normal force and sliding velocity significantly influenced their perception. These results were supported by the tribological measurements on the relative change in friction, the apparent contact area of the finger, and the elastic strain acting on the finger in the sliding direction.

The study by Mun et al. [118] was concerned with the perceptual structure of haptic textures rendered by an electrovibration display. Using 32 textures expressed using regular tessellations of polygons, they obtained a three-dimensional perceptual space that visualized the pairwise perceptual dissimilarities between the textures and their resulting structure. In addition, three perceptual dimensions most adequate to describe the perceptual attributes of the electrovibration textures were found to be rough-smooth, dense-sparse, and bumpy-even.

Perception of Ultrasonic Stimuli. Compared to electrovibration, generating controlled stimuli using ultrasonic actuation to conduct psychophysical experiments is more

difficult. Samur et al. [119] conducted discrimination experiments to evaluate the minimum detectable difference in friction using the tactile pattern display (TPad), actuated at an ultrasonic resonance frequency. The subjects were presented with two stimuli in sequential order and asked to identify the stimulus with higher friction. An average JND of 18% was reported for the friction difference. This study shows the ability of humans to discriminate two surfaces based on friction, but how humans perceive a change in friction cannot be ascertained.

In this regard, Messaoud et al. [120] have evaluated the subjects' performance in detecting a change in friction. Their results showed that the detection rate improves at lower inherent friction between finger and surface, as well as lower finger velocity of 5 mm/s compared to 20 mm/s. They also found that the detection rate is best correlated to friction contrast and a contrast greater than 0.19 is always detectable. It was shown in Saleem et al. [121] that rate of change in tangential force is best correlated with the detection rate of friction change. Later, Saleem et al. [122] also showed that a step increase in friction by ultrasonic actuation casts a stronger perceptual effect as compared to a step fall in friction, supporting the recent results of [117] obtained by electrostatic actuation. Gueorguiev et al. [123] investigated the tactile perception of square pulses displayed by ultrasonic friction modulation and observed that subjects could differentiate between two pulses if the duration and transition time are extended by 2.4 and 2.1 ms, respectively. In another experiment, they found that if the duration between two pulses was shorter than 50 ms, subjects perceived them as a single pulse.

In [124], the authors evaluated the threshold to detect two friction reductions of 100 ms duration, rendered 3 mm apart, using three different ultrasonically actuated surfaces made of aluminum, polypropylene and polyurethane. The rise time of vibration amplitude was controlled at 1.5 ms. The surfaces were passively scanned under the finger at 20 mm/s, while normal force was maintained at 0.7 N. They conducted threshold experiments and measured the vibration thresholds at 75% JND as 0.17, 0.23, 0.27 μm for aluminum, polypropylene and polyurethane, respectively. Furthermore, the detection rate was found to correlate well with the ratio of reduction in tangential force to pre-stimulation tangential force.

The discrimination of periodic gratings, rendered on a touch surface by ultrasonic actuation was investigated in [125]. The surface was vibrated at a frequency of 30 kHz with an amplitude of 1.1 μm . Four standard and eight comparison gratings in square waveform were rendered. The width ratio of high to low friction regimes was always kept constant. The finger velocity was not controlled. The results showed that the difference threshold (JND) increases with spatial period (0.2, 0.32, 0.47 and 0.8 mm for spatial period of 2.5, 3.5, 5 and 10 mm, respectively). Unlike real gratings [44], the Weber fraction remained almost constant (varied between 8 and 10 %).

More recently, Saleem et al [126] investigated our ability to discriminate two consecutive changes in friction (called edges), followed by discrimination and roughness perception of multiple edges (called periodic gratings). The results showed that discrimination of two consecutive edges was

significantly influenced by edge sequence: a step fall in friction (FF) followed by a step rise in friction (RF) was discriminated more easily than the reverse order. On the other hand, periodic gratings generated by displaying consecutive edge sequence of FF followed by RF were perceived with the same acuity as compared to vice versa. They also found that a relative difference of 14% in spatial period was required to discriminate two periodic gratings independent of the edge sequence. Moreover, the roughness perception of periodic gratings decreased with increasing spatial period for the range that they have investigated (spatial period < 2 mm), supporting the results observed by Vardar et al. [113] and Isleyen et al. [115] for friction modulation by electrovibration.

4 HUMAN-MACHINE HAPTICS

Touch-enabled devices such as smartphones and tablets are ubiquitous and used on a daily basis. The devices that are commercially available, however, provide visual and auditory feedback but almost no tactile feedback, even though it is known that tactile feedback improves task performance and realism when interacting with digital data. Moreover, tactile sensation is a significant factor in the preference and positive attitude towards consumer products due to their surface texture. Therefore, a great deal of research is being carried out in recent years to develop and study the techniques that can render tactile information on touch-enabled devices.

This section mainly covers the tactile rendering algorithms for displaying virtual textures and shapes on touch surfaces, the design of user interfaces and experiences with surfaces haptics, and some current applications of surface haptics. A summary of how the technologies of surface haptics, as described in Figure 3, are used to implement these techniques is given in Table 3.

4.1 Tactile Rendering

The rendering of virtual textures, shapes and surface features is important for many applications of surface haptics. Virtual textures can for example be used to simulate material properties or provide informative feedback. Virtual shapes and surface features can similarly be used to augment spatial elements such as buttons or graphical content, indicating location, function, state or other properties. Each type of tactile rendering will be discussed in turn.

4.1.1 Rendering of Virtual Textures

Friction modulation is particularly effective at texture rendering due to its frequency range and inherently passive nature. Virtual textures produced by friction modulation are felt only while a finger brushes against them, thereby increasing their realism. Importantly, this passivity is a fundamental property of friction modulation and is independent of the responsiveness of the display's actuation.

Virtual textures can be synthesized by actuating a friction display with a time-varying periodic signal such as a square or sinusoidal wave. The signal is mapped directly to the driving voltage of an electrostatic display, or modulates the high-frequency carrier signal of an ultrasonic display.

Bau et al. [64] have for example shown that varying the frequency and amplitude of an electrovibrating signal can evoke natural sensations such as touching wood, bumpy leather, paper, a painted wall, or rubber, as well as surface properties such as stickiness, smoothness or pleasantness.

While effective and expressive, time-varying periodic signals have limited realism due to their lack of spatial consistency. Unlike physical textures, a time-varying virtual texture's frequency remains fixed no matter how fast the finger moves against it. To increase realism, friction patterns can instead be registered to spatial features of a surface [66], [127]. A realistic, spatially-invariant grating can for example be produced by activating the friction display as a function of finger position instead of time. The improvements in realism are particularly important for large tactile patterns, but less noticeable for fine patterns for which spatial discrepancies are difficult to perceive [66]. Alternatively, the frequency of the friction signal can be modulated based on the velocity of the finger motion, thereby approximating a spatially-invariant texture [127].

Data-driven approaches have also been used to generate realistic textures. Friction profiles are then modeled from physical textures using measurements made by instrumented probes or tribometers. Jiao et al. [128] developed a data-driven algorithm for rendering virtual textures on electrostatic friction displays. They acquired force and position data while a finger was sliding on 10 different fabric samples to modulate the voltage applied to a touch screen based on the estimated friction coefficients. They conducted psychophysical experiments and showed that the virtual textures were perceptually similar to the corresponding real textures. Osguei et al. [129] proposed an inverse neural network model to learn from recorded real textures. They showed that the voltage signal for electrostatic actuation can be estimated by this model to render virtual textures on touch screen that resemble the real ones. This is one effective technique for data-driven rendering by compensating for the nonlinear dynamics of an electrovibration display [130]. Messaoud et al. [131] used multi-level feature extraction to model the friction profiles of two fabrics, twill and velvet. Camillieri et al. [132] evaluated simulations of these fabric on an ultrasonic friction display and found the reproduction of the coefficient of friction to be accurate, but both similarities and differences in the vibrations induced in the finger. Similarly, brain activation was similar for real and virtual twill fabrics, but there were important differences for velvet.

Wu et al. [133] proposed a rendering method by electrovibration for image-based textures, based on the estimation of local gradients. The gradients were used to map the frequency (texture granularity) and amplitude (texture height) of the voltage signal applied to the touch screen. Their results showed that modulating frequency further improved tactile realism of virtual textures.

Despite these advances, tactile rendering algorithms have yet to reach the realism necessary to simulate a wide range of textures. This is likely due to the limitations in current actuation technology and our understanding of tactile perception, which are further discussed in Section 5

4.1.2 Rendering of Virtual Shapes and Surface Features

In a pilot study, Xu et al. [134] attempted to display raised dots by electrovibration to form Braille cells, but found the results to be difficult or impossible to read. Attempts to identify three simple geometric shapes (circle, square or triangle) rendered by electrovibration similarly resulted in a low success rate of 56% [134]. The difficulty may be largely due to the fact that electrovibration cannot produce a convincing sensation of brushing over a clear edge. Currently, friction modulation produces the same sensation over the entire touch surface. The lack of distributed stimuli under the fingerpad precludes the simulation of a moving edge, and is a likely explanation for the difficulty of identifying shapes with precision.

Despite these technological drawbacks, Kim et al. [135] proposed an algorithm to render 3D features (or bumps) by electrovibration. The algorithm is based on the observation that we can “create a perception of 3D tactile features on a flat touch surface by manipulating only lateral forces, such as friction.” The algorithm maps the gradient of a depth map to the friction display, and normalizes the friction output based on experimental measurements so that the amplitude changes linearly. Their experimental results show that 3D bumps can be perceived by this approach. Osgouei et al. [136] used a similar gradient-based algorithm with electrovibration and asked participants to identify simple geometric patterns such as bumps and holes. They found that participants were unable to do so without contextual information, but had moderate success when this information was given.

Ware et al. [137] have also shown the importance of reducing the need for spatial integration with salient, highly localized features such as tactile edges formed by abrupt changes in friction. Chubb et al. [23] finally demonstrated that surface haptics technologies able to produce net tangential forces (see Section 2.5) can facilitate contour following by producing forces orthogonal to finger motion.

4.2 User Interface Design

In this section, we will see how surface haptics can be effectively integrated in user interfaces. We will first survey the tools available to help with the design of user interfaces with surface haptics. We will then go over the specifics of surface haptics by friction modulation that shape how it can be used in interface design. We will then discuss the performance gains expected with the addition of surface haptics in target acquisition tasks, as well as the design of virtual controls and widgets with surface haptics.

4.2.1 Design Tools

While the deployment of haptic technologies is known to be greatly aided by the availability of effective tools for the different steps of the design process (e.g., sketching, prototyping and production) [138], [139], [140], few such design tools are currently available for surface haptics.

Solutions for sketching friction-based interfaces have been proposed in [141], [142]. Levesque et al., in work partially discussed in [142], experimented with sketches made by chemically etching glass. The etched areas of the glass reduce the perceived friction, thereby simulating the

friction reduction produced by ultrasonic actuation. The resulting patterns, however, were found to be misleading since friction modulation cannot reproduce the distributed tactile stimuli under the fingerpad produced by etched patterns [143]. Potier et al. [141] similarly proposed printing patterns on cards using an ink-jet printer and layers of sticky ink, thereby creating friction patterns. This sketching solution was found to produce similar sensations to those of a friction display for certain types of textures.

Although few details have been published, some companies have also released development kits for electrovibration that include development tools such as Application Programming Interfaces (API). It has also been shown that friction patterns can be specified through bitmapped images (e.g., [144]), greatly facilitating experimentation using creative tools for graphic design.

4.2.2 Designing for Friction Modulation

Designing user interfaces with friction modulation requires careful consideration due to two current limitations of the technology: (1) friction feedback is only felt while the finger slides against the surface and (2) friction modulation is felt identically over the entire surface.

The first limitation implies that friction modulation typically cannot produce feedback for touch and touch-and-hold interactions [64], which require active feedback such as that produced by vibrotactile actuators. This is problematic since these interactions are very common in touch interfaces, e.g., virtual buttons and keyboards that greatly benefit from haptic confirmation feedback. A possible solution consists of combining vibrotactile feedback and friction modulation in the same display, which increases cost and complexity. Alternatively, user interfaces can be redesigned to maximize sliding interactions, e.g. by replacing buttons with sliding toggles [142], [165].

The second limitation imposes constraints on the resolution of spatial effects and support for multi-touch interactions. As previously discussed, friction modulation cannot produce the distributed sensation of an edge moving under the fingertip with current technology. Similarly, friction modulation produces the same haptic feedback on all sliding fingers when performing a multi-touch gesture such as a two-finger pinch or rotation. Bau et al. [64] proposed avoiding this limitation by using anchored gestures or two-handed asynchronous manipulations, in which only one finger moves against the surface and feels the feedback. An anchored variant of a rotation gesture, for example, would leave the thumb fixed and rotate the index finger [64]. This interaction technique was validated experimentally with positive results by Emgin et al. [33]. A two-handed asynchronous manipulation similarly consists of an interaction in which one hand is fixed, while the other moves [64]. It should be noted that these interaction techniques take advantage of the passive nature of friction modulation, and would not be possible with vibrotactile feedback.

4.2.3 Target Acquisition

Pointing at a target is a fundamental task in human-computer interaction that has been extensively studied. The movement time to a target can generally be modelled using Fitt’s law, which relates the movement time to the difficulty

TABLE 3
Use of current technologies in applications on haptic surfaces.

	Normal vibration	Pulses	Lateral vibration	Electrostatic	Ultrasonic	Driving force	Asymmetric friction
Virtual Texture	[130]		[14]	[64], [66], [127], [128], [129], [133]	[131], [132]		
Virtual Shapes				[135], [136]			[30]
Target Acquisition				[145]	[142], [146]		
Buttons	[147], [148], [149], [150], [151], [152], [153], [154], [155], [156], [157]		[158]		[121], [159], [160], [161]	[162]	
Sliding Controls					[142], [163], [33], [164]		

of the task (size and distance of target) and properties of the interaction modality [166]. The effect of surface haptics on target acquisition has been studied, with results suggesting a benefit of the additional feedback.

Levesque et al. [142] investigated the effect of ultrasonic friction modulation on target acquisition for a dragging task. Increasing the friction on a target was shown to improve performance, provided that a single target is displayed. In the presence of spurious targets (distractors), variable friction no longer improved performance but was not detrimental. A supplemental study found evidence for a physical slowdown of the finger with high-friction targets that may explain the performance improvements. Zhang and Harrison [145] performed a similar experiment with electrovibration and found a performance improvement of 7.5% when the entire target is filled with a tactile texture.

Casiez et al. [146] similarly studied the effect of ultrasonic friction modulation on an indirect target acquisition task through a haptic trackpad. The results suggest an improvement of close to 9% in targeting performance in the absence of distractors, and similar performance with distractors. Unlike [142], the effect is believed to be due to information feedback rather a mechanical effect of the friction.

4.2.4 Virtual Controls and Widgets

Virtual controls and widgets are commonly used on touch surfaces but lack the haptic feedback associated with physical controls. This lack of haptic feedback is known to reduce performance and task precision [167] and often forces users to focus their visual attention on the virtual controller. Tangible controls are sometimes used to restore this haptic feedback with a removable physical object (e.g., [168], [169]). SLAP widgets [169], for example, have been shown to outperform their virtual counterparts in terms of task completion time and accuracy. Tangible controls, however, reduce flexibility, cause occlusion, and present many other drawbacks due to their physicality. Surface haptics offers many of the advantages of physical or tangible controls, without these practical limitations. The use of surface haptics for two key controls, buttons and sliding widgets, will be discussed next.

Buttons. Buttons are ubiquitous both in physical and digital interfaces. Pressing a physical button produces a distinct response profile, with a satisfying and informative click

on activation. In contrast, virtual buttons on touchscreen interfaces typically offer limited haptic feedback, if any.

Augmenting a virtual button with haptic feedback has typically been done with low-cost vibration motors and voice coils [147], [148], [149], [150] or piezoelectric actuators [151], [152], [153], [154], [155], [156], [157]. Park et al. [150] investigated the effect of parameters such as the amplitude, duration, carrier signal, envelope function, and type of actuator on the rendering of a virtual button on a mobile device. Their results suggest that a short rise time and short duration are preferred for a pleasant button click. Similarly, Chen et al. [152] found that frequencies of 500 Hz and 125 Hz result in key clicks that are perceived as crisp and dull, respectively. Lylykangas et al. [153] found significant effects of time delay and vibration duration when augmenting clicks with piezoelectric vibrations.

More recently, Sadia et al. [157] displayed vibrotactile feedback through a touch surface with piezoelectric actuators to simulate the feeling of physical buttons. They first recorded and analyzed the force, acceleration, and voltage data from the interactions of twelve participants with three different physical buttons: latch, toggle, and push buttons. Then, a button-specific vibrotactile stimulus was generated for each button by modulating the recorded acceleration signal with the resonance frequency of the surface. In their user experiments, participants were able to match the three digital buttons with their physical counterparts with a success rate of 83%.

Although button clicks are most commonly produced with vibration feedback, it has been shown that the effect can be simulated by friction modulation on ultrasonic devices [121], [159], [160], [161]. Tashiro et al. [159] reproduced the sensation of buckling and restitution of a physical button using a Langevin-type ultrasonic transducer and explained the sensation by the momentary finger slippage as friction is reduced. Monnoyer et al. [161], on the other hand, explains the clicking sensation by the accumulation and sudden release of stress in the fingerpad. The sensation of click has also been optimized based on the finger impedance [160] and the rate of change in normal force [122].

Sliding Controls. While simulating button clicks may be possible with certain variants of friction modulation, this type of surface haptics is typically best used to augment controls such as knobs and sliders that require relative motion between the finger and the interactive surface.

Emgin et al. [33] rendered a virtual knob with tactile feedback on the HapTable, a large electrostatic display. Friction feedback such as detents was produced as users turned the knob to select items in a menu. While performance improvements could not be demonstrated, the haptic feedback was found to significantly improve the subjective experience of the participants. Giraud et al. [164] similarly implemented a haptic knob with ultrasonic friction modulation and found improvements in task accuracy when selecting an item in a scrolling list.

As further discussed below, Levesque et al. [142], [163] also experimented with the design of sliding controls with ultrasonic friction modulation on touchscreens. They first designed and evaluated a number of sample applications using sliding gestures (such as moving the wheels of an alarm clock) [142], before evaluating the feasibility of several scrolling interactions [163].

4.3 Applications

Several researchers have explored applications of surface haptics, and particularly the novel possibilities offered by friction modulation.

Bau et al. [64] proposed a wide range of applications of surface haptics by vibration or friction modulation, with the expectation of better results with electrovibration due to its frequency range and uniform response over a surface. The applications include the simulation of realistic tactile effects (e.g., the friction between a brush and a canvas), non-visual information layers (e.g., a tactile overlay indicating radiation intensity over the image of a star), augmented GUI widgets (e.g., sliders or scrolling lists with tactile feedback), direct manipulation (e.g., friction on drag & drop operations), or rubbing interactions (e.g., erasing by repeated brushing). Some of these application concepts were implemented on an electrovibrating surface, such as feeling different textures, dragging a race car along a track, and editing a picture by rubbing.

Levesque et al. [142] explored the design space of ultrasonic friction reduction for touchscreens. They designed four simple applications demonstrating several use cases for friction: an alarm clock, a file manager, a game and a text editor. The effects included clicks when turning the wheels of the alarm clock, resistance when dragging a file over a folder, impacts as a ball is hit in the game, and a "pop-through" sensation when displacing words in the text editor. The resulting user experiences were evaluated quantitatively and qualitatively by having participants briefly interact with the sample applications with and without haptic feedback. The results suggest that the tactile feedback had a positive impact on enjoyment, engagement and the sense of realism.

In follow-up work, Levesque et al. [163] further explored the applications of friction modulation for scrolling interactions on touchscreens. They developed five scenarios exemplifying interaction styles and applications such as scrolling in a webpage or adjusting a numerical value on a slider. Five experiments were run to understand the feasibility of the different required features, such as being able to identify and count detents, and perceive their density. The results were recommendations for design based on the strengths and limitations that were identified.

Although few details are publicly available, some companies have also developed demonstrators for surface haptics. Levesque et al. [165], for example, describe a demonstration application inspired by illustrated children's books with tactile features, such as fabrics, fur and moving parts. The virtual book contains five interactive pages exemplifying the strengths of electrovibration: four animals with different textures, from soft fur to scales; a block of ice that can be rubbed away, revealing a monster; a suspended car that can be released by cutting or sawing ropes; a sliding character that brushes against the page as it is moved; and a safe that can be opened by turning a dial. Of particular note, activation of the feedback is controlled by pulling on a ribbon instead of pressing on a button, thereby allowing friction feedback to be produced.

Mullenbach et al. [144] explored applications of ultrasonic friction modulation for affective communication. Three applications were implemented and evaluated: a text messaging application in which messages can be augmented with one of 24 friction patterns; an image sharing application in which an image can be annotated with friction patterns; and a virtual touch application in which remote partners can feel each other's traces against a touchscreen. The results suggest that the participants, which included strangers and intimate couples, viewed surface haptics as an effective way to communicate emotional information to a remote partner.

Applications of surface haptics for the visually impaired have also been explored. Xu et al. [134] experimented with electrovibration to produce Braille and tactile graphics. Since electrovibration cannot produce a pattern smaller than the fingertip, Braille was presented through frequency modulation, temporal mapping, or enlargement. The results were found to be difficult to read. Attempts to display simple geometrical shapes (circle, square and triangle) similarly resulted in relatively low performance (56% identification rate), likely due to the difficulty of representing sharp edges with electrovibration. Israr et al. [170] similarly used electrovibration for sensory substitution, allowing visually impaired users to aim a touchscreen at a scene and feel its content through friction patterns. The device was tested by having two visually impaired participants search for an object in a room, with positive results. Lim et al. [171] designed and prototyped a mobile application, called TouchPhoto, that allows a visually-impaired user to take photographs independently while recording auditory tags that are useful for recall of the photographs' content. TouchPhoto also provides a system with which the user can perceive the main landmarks of a person's face in the photograph by touch using an electrovibration display. However, a user study showed that the effectiveness of haptics had considerable room for improvement.

Bau et al. [66] expanded the use of electrovibration beyond touchscreens and explored applications of tactile feedback for real-world objects. The work was positioned as a form of tactile augmented reality, in which the tactile feeling of real-world objects can be augmented with virtual tactile effects. Sample applications include augmented surfaces (e.g., tactile feedback on a projected wall display), see-through augmented reality with tactile feedback on real-world objects, and tactile feedback for interactions with

tangibles. Further concepts were also proposed, such as adding tactile textures to physical prints, communicating personalized, private messages in public touch displays, and assistive applications (e.g., guiding a visually impaired person with a tactile guide against a wall).

5 DISCUSSION AND CHALLENGES AHEAD

5.1 Challenges

Currently, there are three prominent actuation methods for displaying tactile feedback through a touch surface; vibrotactile, electrostatic, and ultrasonic. Each actuation method has its own advantages and disadvantages. However, independent of the actuation method being used, there are a number of features *desired* for surface haptic displays as listed below. Implementation of some is highly challenging with the technology available today, but necessary to make surface haptics displays reach the mass market in the near future.

High Transparency. The tactile surface should be transparent to allow visual information to be displayed to the user in tandem with tactile feedback. This puts some constraints on material properties of the touch surface as well as the type of actuators and actuation methods used for tactile feedback. For example, it is known that a brittle and transparent glass surface vibrates less than a ductile and non-transparent metal surface of the same size and shape. Hence, more powerful actuators are required to display vibrotactile tactile feedback on a glass surface with sufficient amplitude. Partially for the same reason, the zones where the friction reduction is achieved are limited in ultrasonic actuation.

Large Tactile Interaction Area. The interaction area should be sufficiently large to display effective tactile feedback to the users as they interact with digital data. However, achieving a large tactile area is not always possible due to the limitations of the current technology. For example, ultrasonic actuation of a touch surface at a certain resonance frequency leads to a limited number of effective zones for friction modulation due to the certain mode shape at that frequency based on the dimensions and material properties of the surface. Similarly, the number of potential problems increases with the size of capacitive touchscreens used for electrostatic actuation due to the difficulties in manufacturing them. Large capacitive touch screens may cause non-uniform distribution of charges on its surface as a result of the variations in the thickness of conductive and insulator layers and also the non-visible cracks in the insulator layer.

Simultaneous Tactile Feedback Displayed in Different Directions. It is desired to display tactile feedback in the directions normal and tangential to the tactile surface simultaneously. However, it is not always possible to achieve tactile effects in all directions using a single actuation technique today. For example, it is currently not possible to generate tactile effects in the normal direction using electrostatic actuation while vibrotactile actuation is typically preferred over the others for this purpose.

Simultaneous Tactile Feedback Stimulating Different Receptors. The current actuation technology is limited to the stimulation of rapidly adapting mechanoreceptors mostly. For example, due to the nature of electrovibration, it is

not possible to feel bumps or edges when the finger is stationary. In addition to the four major mechanoreceptors mentioned in Section 3, the human finger is equipped with thermoreceptors, nociceptors, and chemoreceptors. Among those, there are a limited number of studies on stimulating thermoreceptors by modulating the temperature of a surface while stimulating mechanoreceptors. For example, Guo et al. [172] investigated the effect of temperature on tactile perception of stimulus displayed by electrovibration and reported that the absolute detection threshold decreases with increasing temperature.

Low Power Consumption. The tactile surface should not require a significant energy to actuate. One of the challenges with the current surface haptics displays is the high energy requirements, which hinders them to reach the mass market. For example, both the ultrasonic and electrostatic actuation techniques require significantly high voltages to operate, compared to the voltage requirements of low-cost vibration motors typically used in mobile devices today. The frequency of stimulation is another factor affecting the energy cost. For example, in order to display virtual textures, a low frequency texture signal is typically modulated with a high frequency carrier signal close to the sensitive frequencies of the human vibrotactile system to boost the tactile effect. While amplitude modulation is beneficial for effective rendering of complex tactile signals, it is disadvantageous in terms of the energy cost.

Easy Integration and Compact Design. It should be easy to integrate a tactile surface into current devices such as mobile phones and tablets. For those systems, for example, the number of moving parts needs to be reduced to prevent dirt and dust from penetrating into the devices. The geometry and material properties of the tactile surface, the location of actuators attached to it, and the housing in which it is placed all have significant influence on the ease of integration, but also the tactile feedback capacity of the device. For example, in the case of vibrotactile and ultrasonic actuation, the boundary conditions influence the out of plane and in-plane resonance frequencies and mode shapes of the tactile surface. In the case of electrostatic actuation on the other hand, where there is no mechanical vibration, the thickness of insulator layer has been shown to affect the magnitude of friction force displayed to the user [89]. While it is possible to reduce the applied voltage by using a thinner insulator, the thickness is still limited by the breakdown voltage. The breakdown voltage is the maximum voltage difference that can be applied across the conductive layers (ITO and the finger) before the insulator collapses and conducts current.

Realistic Tactile Effects. Not only the richness of tactile effects, but the flexibility in generating them and their realism are also highly important. Again, due to the limitations in current technology, it is difficult to achieve all together. For example, in texture rendering, it is not possible to display texture topography directly by modulating friction in the tangential direction using ultrasonic or electrostatic actuation. As a result, tactile perception of virtual textures displayed on touch surfaces via those methods is expected to be different than tactile perception of real ones [115], [126]. Moreover, the range for the modulated friction coefficient is limited in both methods though their coupling results in a larger range [173]. Even if we have a larger

bandwidth, the realistic rendering of virtual textures on touch surfaces will be still challenging since the textures in nature are complex and come in various forms. Recently, a tri-modal tactile display was developed by integrating electrostatic, ultrasonic, and vibrotactile actuation methods [174]. The authors claim that this approach leads to significant improvements both in recognition rate and tactile perception of tactile images.

Localized, Distributed, and Multi-Finger Interactions.

Future surface haptics applications will include multiple tactile stimuli displayed simultaneously or consecutively to a single finger or multiple fingers through a touch surface. However, there are technological challenges in displaying localized tactile stimuli through a touch surface in multi-finger applications. For example, in the case of vibrotactile feedback in the normal and tangential directions, it is highly difficult to control the propagation of the vibration waves to create localized effects, though some solutions have been already suggested in the literature as discussed in Section 2.3.2. These solutions, however, require multiple actuators with independent control. The challenge is to be able to adapt them to the localization of the tactile stimuli, to the surface geometry, and to the number of fingers touching the surface. It is therefore essential to design control electronics that can address the aforementioned issues at low cost, yet ensuring fast response.

On the other hand, in the case of electrovibration, current design and manufacturing steps of multi-finger capacitive touch screens (i.e., projected capacitive) introduce some difficulties. Today, most of the research groups working on surface haptics use a single-touch capacitive screen (i.e., surface capacitive) to avoid those difficulties. A surface capacitive touchscreen uses a single layer of conductive ITO with a simple electrode pattern on top of it and passing through its edges. Hence, the voltage applied to the conductive ITO layer generates uniform tactile effects over its surface. If the finger position is tracked by means of the touch screen itself or an external sensor such as an IR frame, then different tactile effects can be displayed to the user based on the acquired finger position, creating an illusion of localized tactile feedback. However, this illusion breaks down quickly as soon as the user contacts the surface with more than one finger. In a true multi-finger case, each finger has to be stimulated with a different and independent tactile signal. In order to demonstrate the concept of true multi-touch haptic interactions, for example, Emgin et al. [175] developed a custom solution. They ablated a surface capacitive touch screen using a UV laser to pattern a grid of conductive indium tin oxide (ITO) cells (called haptiPads by the authors) and thin ITO wires carrying electric current to the cells for independent electrostatic actuation. This approach leads to localized and multi-finger haptics, but the process of constructing haptiPads is tedious and error-prone in a university laboratory. Perhaps, a better alternative is to display tactile effects through a projected capacitive screen. In fact, surface capacitive touch screens are already replaced by projected-capacitive touchscreens in the market since the latter allows simultaneous sensing of multi-finger contacts. Projected-capacitive screens use one or more etched ITO layers forming multiple horizontal (X) and vertical (Y) electrodes in various patterns to detect multi-finger contact

interactions. Obviously, when a voltage applied to a single horizontal/vertical electrode, electrovibration is generated along a thin row/column on the touch screen. In order to create localized stimulation, Haga et al. [176] used the beat phenomenon. When two sinusoidal signals with frequencies of f_1 and f_2 are superposed, the resulting “beat” signal will have major frequency components at $(f_1 + f_2)/2$ and $(f_1 - f_2)/2$. They applied AC voltages with frequencies of 1000 Hz and 1240 Hz to an X and Y electrodes to create an oscillating electrostatic force at frequencies of 2240 Hz (2×1120 Hz) and 240 Hz (2×120 Hz). The first frequency is outside the detectable range of human vibrotactile sensing while the latter is optimal.

If the number of X and Y electrodes are sufficiently high and can be actuated individually, then we can talk about *distributed* surface haptics. Unfortunately, current surface haptics displays lack a distributed presentation. This means that an edge smaller than the size of a finger cannot be displayed when it is touched with one finger.

5.2 Future Outlook

Nowadays, touch surfaces are an integral part of our mobile phones, smart watches, tablets, laptops, ATMs, tabletops, vending machines, electronic kiosks, and car navigation systems. These surfaces allow us to directly manipulate digital content via touch gestures. However, the lack of sophisticated tactile feedback displayed through touch surfaces results in a decrease in user experience quality and even task performance. Moreover, it is also important to realize that most of our sensory communication with the aforementioned electronic devices today is through visual and auditory channels, which are highly overloaded. Alternatively, some of the information can be displayed through the haptic channel in order to alleviate the perceptual and cognitive load of the user. In this regard, touch surfaces appear to be the right user interface and the research on surface haptics could have a significant return on investment in the near future. The largest impact is naturally expected to be in mobile devices. In this domain, gesture-based interaction with touch surfaces is already the primary user interface and makes it easier to access and manipulate digital data. With the integration of tactile feedback in existing gestures such as tap, slide, click, drag, pinch, twirl, and swipe, our performance and confidence in activating, selecting, moving, zooming, rotating, and adjusting digital content is expected to improve. In addition, tactile feedback on mobile devices will enable the visually impaired and blind to access digital content. In fact, even sighted people may rely on tactile feedback in difficult ambient lighting conditions.

However, we anticipate that surface haptics in the future will not be restricted to the touch surfaces of electronic devices only but will be available in any flat, curved, and flexible physical surface made of hard or soft material having some form of embedded computational capability. In particular, emerging new material technologies can bridge the electronic and mechanical domains (see a recent review in [177]), enabling more sophisticated surface displays.

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